

# WIMP Dark Matter and Baryogenesis

Pei-Hong Gu<sup>1,\*</sup>, Manfred Lindner<sup>1,†</sup>, Utpal Sarkar<sup>2,‡</sup> and Xinmin Zhang<sup>3§</sup>

<sup>1</sup>*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

<sup>2</sup>*Physical Research Laboratory, Ahmedabad 380009, India*

<sup>3</sup>*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

In the present universe visible and dark matter contribute comparable energy density although they have different properties. This coincidence can be elegantly explained if the dark matter relic density, originating from a dark matter asymmetry, is fully determined by the baryon asymmetry. Thus the dark matter mass is not arbitrary, rather becomes predictive. We realize this scenario in baryon(lepton) number conserving models where two or more neutral singlet scalars decay into two or three baryonic(leptonic) dark matter scalars, and also decay into quarks(leptons) through other on-shell and/or off-shell exotic scalar bilinears. The produced baryon(lepton) asymmetries in the dark matter scalar and in the standard model quarks(leptons) are thus equal and opposite. The dark matter mass can be predicted in a range from a few GeV to a few TeV depending on the baryon(lepton) numbers of the decaying scalars and the dark matter scalar. The dark matter scalar can interact with the visible matter through the exchange of the standard model Higgs boson, opening a window for the dark matter direct detection experiments. These models also provide testable predictions in the searches for the exotic scalar bilinears at LHC.

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*Introduction:* Cosmological observations indicate that dark and visible matter have different properties but contribute comparable energy density to the present universe [1]. This intriguing coincidence indicates a common origin of the dark and visible matter. The visible matter exists in the present universe due to a matter–antimatter asymmetry, which is the same as the baryon asymmetry. The dark matter relic density may also be an asymmetry between the dark matter and antimatter [2, 3]. If the dark matter asymmetry is further determined by the baryon asymmetry, we can naturally explain the coincidence between the visible and dark matter. In this case the dark matter mass is not arbitrary but predictive and depends on the well known nucleon mass. In the existing models of the dark matter asymmetry, the dark matter mass is expected to be in the GeV scale unless we abandon the requirement of determining the baryon asymmetry in terms of the dark matter asymmetry.

In this paper we propose a novel idea to predict the dark matter mass in a range from the GeV scale to the TeV scale although the dark matter asymmetry is fully determined by the baryon asymmetry. In our models, the baryon(lepton) asymmetry in a dark matter scalar [4] is equal but opposite to the baryon(lepton) asymmetry in the standard model (SM) quarks(leptons). Although the total baryon(lepton) asymmetry is zero, only the baryon(lepton) asymmetry in the SM quarks(leptons) can be partially converted to the final baryon asymmetry because the baryon(lepton) asymmetry in the dark matter scalar has no effect on the sphaleron processes [5]. As for the dark matter asymmetry, it is the ratio of the baryon(lepton) asymmetry in the dark matter scalar over the baryon(lepton) number of the dark matter scalar. We thus can expect a smaller dark matter asymmetry and a heavier dark matter mass as long as the dark matter

scalar has a proper baryon(lepton) number. This can be achieved if the decaying scalars directly decay into two or three dark matter scalars while their decays into a number of the SM quarks(leptons) are mediated by some on-shell and/or off-shell exotic scalar bilinears, which couple to two SM quarks(leptons). Our dark matter scalar is a typical weakly interacting massive particle (WIMP) as it interacts with the visible matter through the exchange of the SM Higgs boson.

When we were finalizing our manuscript, Buckley and Randall [6] have discussed the same idea to predict a bigger dark matter mass from a smaller dark matter asymmetry. However, our simple mechanism for suppressing the dark matter asymmetry is different from theirs.

*The Models:* We first construct the baryon number conserving models. We introduce two color-triplet and iso-singlet scalars  $\delta(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$  and  $\omega(\mathbf{3}, \mathbf{1}, \frac{2}{3})$ , both of which carry a baryon number  $B = -\frac{2}{3}$ . Their allowed Yukawa couplings to the SM quark doublets  $q_L(\mathbf{3}, \mathbf{2}, \frac{1}{6})$  and singlets  $u_R(\mathbf{3}, \mathbf{1}, \frac{2}{3})$  and  $d_R(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$  are given by

$$\mathcal{L} \supset -f_\delta \delta \bar{q}_L^c i \tau_2 q_L - f'_\delta \delta \bar{u}_R^c d_R - f_\omega \omega \bar{d}_R^c d_R + \text{H.c.} \quad (1)$$

We also introduce a neutral singlet scalar  $X_1(\mathbf{1}, \mathbf{1}, 0)$  with a baryon number  $B = 2$ . So, the following scalar interaction is allowed as it conserves the baryon number,

$$\mathcal{L} \supset -\kappa_1 X_1 \omega \delta^2 + \text{H.c.} \quad (2)$$

There can be more neutral singlet scalars  $X_i(\mathbf{1}, \mathbf{1}, 0)$  with the baryon numbers defined by

$$\mathcal{L} \supset -\sum_{i=2}^n \kappa_i X_i^* X_{i-1}^{a_{i-1}} + \text{H.c. with } a_{i-1} = 2 \text{ or } 3. \quad (3)$$

Finally we introduce another neutral singlet scalar  $\chi(\mathbf{1}, \mathbf{1}, 0)$ . In the case without  $X_i(i = 2, \dots, n)$ , we con-

sider the baryon number conserving interaction between  $\chi$  and  $X_1$ ,

$$\mathcal{L} \supset -\gamma_1 X_1^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3. \quad (4)$$

In the presence of  $X_i (i = 2, \dots, n)$ , we consider the baryon number conserving interaction between  $\chi$  and  $X_n$ ,

$$\mathcal{L} \supset -\gamma_n X_n^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3 \text{ but } b \neq a_{n-1}. \quad (5)$$

Here the choice  $b \neq a_{n-1}$  is to forbid the couplings  $\mathcal{L} \supset -\alpha \chi^* X_{n-1} - \beta (\chi^* X_{n-1})^2 + \text{H.c.}$ . We emphasize that by proper choice of the parameters in the scalar potential the neutral scalars  $X_i$  and  $\chi$  will not develop any vacuum expectation values (VEVs) to break the baryon number. So, we can have a stable  $\chi$  to act as the dark matter. In a similar fashion we could consider color-sextet scalars to implement this scenario.

We also construct models with conserving lepton number. We introduce an iso-triplet scalar  $\xi(\mathbf{1}, \mathbf{2}, 1)$  with a lepton number  $L = -2$ . The triplet scalar  $\xi$  thus can have the Yukawa couplings with the SM lepton doublets  $l_L(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ ,

$$\mathcal{L} \supset -f_\xi \bar{l}_L^c i \tau_2 \xi l_L + \text{H.c.} \quad (6)$$

We then introduce a neutral singlet  $X_1(\mathbf{1}, \mathbf{1}, 0)$  with a lepton number  $L = 2$  and other neutral singlet scalars  $X_i(\mathbf{1}, \mathbf{1}, 0) (i = 2, \dots, n)$  with the lepton numbers defined by

$$\mathcal{L} \supset -\sum_{i=2}^n \kappa_i X_i^* X_{i-1}^{a_{i-1}} + \text{H.c. with } a_{i-1} = 2 \text{ or } 3. \quad (7)$$

The singlet scalar  $X_1$  has a lepton number conserving interaction with the triplet scalar  $\xi$  and the SM Higgs doublet  $\phi(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ ,

$$\mathcal{L} \supset -\kappa_1 X_1 \phi^T i \tau_2 \xi \phi + \text{H.c.} \quad (8)$$

We further introduce another neutral singlet scalar  $\chi(\mathbf{1}, \mathbf{1}, 0)$  with the lepton number defined by

$$\mathcal{L} \supset -\gamma_1 X_1^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3 \quad (9)$$

in the absence of  $X_i (i = 2, \dots, n)$ , or by

$$\mathcal{L} \supset -\gamma_n X_n^* \chi^b + \text{H.c. with } b = 2 \text{ or } 3 \text{ but } b \neq a_{n-1} \quad (10)$$

in the presence of  $X_i (i = 2, \dots, n)$ . The singlet  $\chi$  can keep stable to be the dark matter as a result of the unbroken lepton number. We can replace the triplet scalar  $\chi$  by two charged singlet scalars  $\zeta(\mathbf{1}, \mathbf{1}, 1)$  and  $\varrho(\mathbf{1}, \mathbf{1}, 2)$ , both of which carry a lepton number  $L = -2$ , to construct the lepton number conserving models. Specifically, the interactions (6) and (8) should be replaced by

$$\mathcal{L} \supset -f_\zeta \zeta \bar{l}_L^c i \tau_2 l_L - f_\varrho \varrho \bar{e}_R^c e_R - \kappa_1 X_1 \varrho^* \zeta^2 + \text{H.c.}, \quad (11)$$

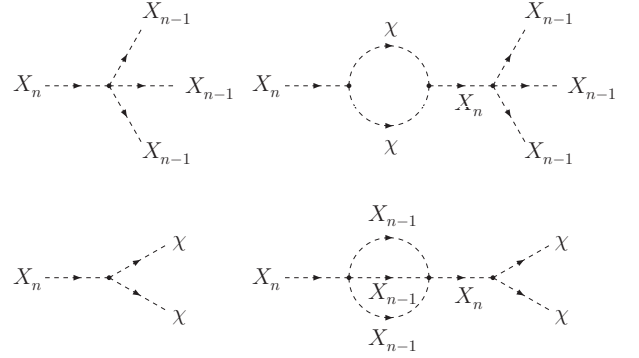


FIG. 1: An example of the decays of the singlet scalars  $X_n$  for generating the baryon(lepton) asymmetries in the subsequently decaying scalar  $X_{n-1}$  and in the dark matter scalar  $\chi$ . The subsequent decays into the SM quarks(leptons) are not shown for simplicity.

with  $e_R(\mathbf{1}, \mathbf{1}, -1)$  being the right-handed charged leptons.

*Dark Matter Asymmetry and Mass:* In the above baryon(lepton) number conserving models, the neutral singlet scalars  $X_k (k = 1 \text{ or } n)$  have two decay channels: one is into two or three dark matter scalars  $\chi$ , the other one is into a number of the SM quarks(leptons) through other on-shell and/or off-shell scalars. In the presence of two or more  $X_k (k = 1 \text{ or } n)$ , we can obtain a baryon(lepton) asymmetry in the SM quarks(leptons) and an equal but opposite baryon asymmetry in the dark matter scalar  $\chi$ ,

$$\varepsilon_\chi^{B(L)} = -\varepsilon_{\text{SM}}^{B(L)}. \quad (12)$$

This can be understood from Fig. 1 where we show an example of the decays of  $X_n$ . Since the baryon(lepton) asymmetry in the dark matter scalar has no effect on the sphaleron processes, the baryon(lepton) asymmetry in the SM quarks(leptons) can be partially converted to the final baryon asymmetry [5],

$$\eta_B = \frac{28}{79} \varepsilon_{\text{SM}}^B \text{ or } \eta_B = -\frac{28}{79} \varepsilon_{\text{SM}}^L. \quad (13)$$

This is like the essence of the leptogenesis [7] with Dirac neutrinos [8]. Here the other interactions that violate the SM baryon and/or lepton number have been assumed to decouple before the above baryogenesis epoch. We also have assumed that the baryon(lepton) asymmetry is produced before the electroweak phase transition. This assumption is not necessary for the baryon number conserving models, i.e. the coefficient  $\frac{28}{79}$  should be absent if the baryon asymmetry is produced after the electroweak phase transition. We shall not consider this possibility for simplicity.

As for the dark matter asymmetry, it is the ratio of the baryon(lepton) asymmetry in the dark matter scalar over

the baryon(lepton) number of the dark matter scalar,

$$\eta_\chi = \begin{cases} \pm \frac{b}{2} \varepsilon_\chi^{B(L)} & \text{for } k = 1, \\ \pm \frac{b}{2a_1 a_2 \dots a_{n-1}} \varepsilon_\chi^{B(L)} & \text{for } k = n. \end{cases} \quad (14)$$

Here the choice of the sign + or - depends on the definition of the dark matter and dark antimatter, i.e.  $\chi$  is the dark matter or the dark antimatter. If the dark matter asymmetry is responsible for the dark matter relic density, we can read

$$\Omega_B : \Omega_\chi = \eta_B m_N : \eta_\chi m_\chi, \quad (15)$$

where  $m_N$  is the nucleon mass and will be taken to be  $m_N = \frac{1}{2}(m_p + m_n) = 939 \text{ MeV}$  by ignoring the tiny difference between the proton and neutron masses. Since the fractions of the visible and dark matter in the present universe has been precisely measured, i.e. [1]

$$\begin{aligned} \Omega_B h^2 &= 0.02273 \pm 0.00062, \\ \Omega_\chi h^2 &= 0.1099 \pm 0.0062, \end{aligned} \quad (16)$$

we can predict the dark matter mass by

$$m_\chi = \frac{\Omega_\chi}{\Omega_B} \frac{\eta_B}{\eta_\chi} m_N. \quad (17)$$

The above predictive dark matter mass can be in a range from the GeV scale to the TeV scale by choosing the baryon(lepton) number of the decaying neutral scalars and the dark matter scalar. For example, in the case with  $k = 1$ , we read

$$m_\chi = \begin{cases} 1.07 \text{ GeV} & \text{for } b = 3, \\ 1.61 \text{ GeV} & \text{for } b = 2. \end{cases} \quad (18)$$

It is possible to predict a heavier dark matter mass by choosing a bigger baryon(lepton) number of the dark matter scalar. For example, by taking  $a_1 = \dots = a_{n-1} = 3$  and  $b = 2$ , we read

$$m_\chi = \begin{cases} 4.83 \text{ GeV} & \text{for } n = 2, \\ 14.5 \text{ GeV} & \text{for } n = 3, \\ 43.4 \text{ GeV} & \text{for } n = 4, \\ 130 \text{ GeV} & \text{for } n = 5, \\ 391 \text{ GeV} & \text{for } n = 6, \\ 1.17 \text{ TeV} & \text{for } n = 7. \end{cases} \quad (19)$$

*Dark Matter Direct Detection:* The dark matter scalar  $\chi$  has a quartic coupling with the SM Higgs doublet  $\phi$ ,

$$\mathcal{L} \supset -\lambda_{\chi\phi} \chi^* \chi \phi^\dagger \phi, \quad (20)$$

and hence a trilinear coupling with the SM Higgs boson,

$$\mathcal{L} \supset -\lambda_{\chi\phi} v h \chi^* \chi \quad \text{with} \quad \phi = \begin{bmatrix} \frac{1}{\sqrt{2}}(v + h) \\ 0 \end{bmatrix}. \quad (21)$$

The t-channel exchange of the SM Higgs boson  $h$  will result in an elastic scattering of the dark matter  $\chi$  on the nucleon  $N$ . The dark matter scattering cross section would be

$$\sigma_{\chi N \rightarrow \chi N} = \frac{\lambda_{\chi\phi}^2}{4\pi} \frac{f^2 m_N^2 \mu_r^2}{m_h^4 m_\chi^2}, \quad (22)$$

where  $\mu_r = m_\chi m_N / (m_\chi + m_N)$  is the reduced mass, the factor  $f$  in the range  $0.14 < f < 0.66$  has a central value  $f = 0.30$  [9]. The scattering cross section (22) is strongly constrained by the dark matter direct detection experiments [10]. We find for the predictive dark matter masses (18) and (19), the dark matter scattering cross section can fulfill the experimental results for an appropriate  $\lambda_{\chi\phi}$ . For example, by fixing  $m_h = 120 \text{ GeV}$  and  $f = 0.3$ , we read

$$\sigma_{\chi N \rightarrow \chi N} = \begin{cases} \frac{\lambda_{\chi\phi}^2}{1} \cdot 2.6 \cdot 10^{-39} \text{ cm}^2 & \text{for } m_\chi = 1.07 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{1} \cdot 1.6 \cdot 10^{-39} \text{ cm}^2 & \text{for } m_\chi = 1.61 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{1} \cdot 3.1 \cdot 10^{-40} \text{ cm}^2 & \text{for } m_\chi = 4.83 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{0.1} \cdot 4.4 \cdot 10^{-42} \text{ cm}^2 & \text{for } m_\chi = 14.5 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{0.01} \cdot 5.3 \cdot 10^{-44} \text{ cm}^2 & \text{for } m_\chi = 43.4 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{0.05} \cdot 3.0 \cdot 10^{-44} \text{ cm}^2 & \text{for } m_\chi = 130 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{1} \cdot 6.8 \cdot 10^{-44} \text{ cm}^2 & \text{for } m_\chi = 391 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{5} \cdot 3.8 \cdot 10^{-44} \text{ cm}^2 & \text{for } m_\chi = 1.17 \text{ TeV}. \end{cases} \quad (23)$$

*Dark Matter and Antimatter Annihilation:* If the dark matter asymmetry is expected to account for the dark matter relic density, a fast annihilation between the dark matter and antimatter should be guaranteed to dilute the thermally produced relic density. In other words, the annihilation cross section should be much bigger than the typical value  $\sim 1 \text{ pb}$  for thermally generating the dark matter relic density. We check for a dark matter mass above a few hundred GeV, the dark matter scalar can annihilate very fast into the SM fields through its quartic coupling with the SM Higgs doublet. For example, we have

$$\langle \sigma v \rangle = \frac{\lambda_{\chi\phi}^2}{16\pi m_\chi^2} = \begin{cases} \frac{\lambda_{\chi\phi}^2}{1} \cdot 50.7 \text{ pb} & \text{for } m_\chi = 391 \text{ GeV}, \\ \frac{\lambda_{\chi\phi}^2}{5} \cdot 28.3 \text{ pb} & \text{for } m_\chi = 1.17 \text{ TeV}. \end{cases} \quad (24)$$

As for the case with a dark matter mass around or below the SM Higgs mass, the dark matter annihilation into the SM fields should be suppressed by the quartic coupling  $\lambda_{\chi\phi}$  (constrained by the dark matter direct detection experiments) and/or the Yukawa couplings of the SM fermions. In this case, we need to introduce other fields to enhance the annihilation between the dark matter and antimatter. For example, we can consider a Higgs

singlet  $\sigma(\mathbf{1}, \mathbf{1}, 0)$  to break a global symmetry at the electroweak scale, i.e.

$$\sigma = \frac{1}{\sqrt{2}}(v' + h')e^{i\frac{\phi}{v'}}. \quad (25)$$

The dark matter scalar  $\chi$  has a quartic coupling with  $\sigma$ ,

$$\mathcal{L} \supset -\lambda_{\chi\sigma}\chi^*\chi\sigma^*\sigma, \quad (26)$$

so that it can significantly annihilate into the massless Goldstone  $\rho$ . For example, by fixing  $m_{h'} = 70$  GeV, we have

$$\langle\sigma v\rangle = \frac{\lambda_{\chi\sigma}^2 m_\chi^2}{4\pi m_{h'}^4} = \begin{cases} \frac{\lambda_{\chi\sigma}^2}{10} \cdot 14.8 \text{ pb} & \text{for } m_\chi = 1.07 \text{ GeV}, \\ \frac{\lambda_{\chi\sigma}^2}{5} \cdot 16.7 \text{ pb} & \text{for } m_\chi = 1.61 \text{ GeV} \\ \frac{\lambda_{\chi\sigma}^2}{1} \cdot 30.1 \text{ pb} & \text{for } m_\chi = 4.83 \text{ GeV}. \end{cases} \quad (27)$$

Here we simply ignored the mixing between the SM Higgs boson  $h$  and the non-SM one  $h'$  which is from the quartic coupling,

$$\mathcal{L} \supset -\lambda_{\sigma\phi}\sigma^*\sigma\phi^\dagger\phi. \quad (28)$$

The  $h - h'$  mixing will not significantly change the annihilation cross section but will have interesting implications on the SM Higgs searches at the colliders [11]. The global symmetry breaking can be related to the Dirac [12, 13] seesaw [14] mechanism for generating the small Dirac neutrino masses. For example, we consider [13]

$$\mathcal{L} \supset -y_\nu \bar{l}_L \eta \nu_R - \mu \sigma \eta^\dagger \phi + \text{H.c.}, \quad (29)$$

where  $\nu_R(\mathbf{1}, \mathbf{1}, 0)$  denotes the right-handed neutrinos and  $\eta(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$  is a new Higgs doublet. The global symmetry is imposed in the way that  $\nu_R^c$ ,  $\eta$  and  $\sigma$  carry the same quantum numbers. For  $\langle\sigma\rangle \sim \langle\phi\rangle$ , we can obtain the desired neutrino masses for  $y_\nu = \mathcal{O}(1)$  and  $\mu \lesssim m_\eta = \mathcal{O}(10^{14} \text{ GeV})$ . Note the contribution from  $\eta$  to the Goldstone  $\rho$  should be negligible since  $\langle\eta\rangle \ll \langle\sigma\rangle$ .

*Summary:* In this paper we proposed a novel mechanism to predict the dark matter mass in the range from the GeV scale to the TeV scale. In our scenario, the dark matter relic density is a nonthermally [15] produced dark matter asymmetry determined by the baryon asymmetry so that we can naturally explain the comparable energy density of the visible and dark matter in the present universe. The dark matter mass is thus predictive rather than arbitrary. In particular, the predictive dark matter mass should depend on the baryon(lepton) number of the dark matter field since the dark matter asymmetry is the ratio of the baryon(lepton) asymmetry in the dark matter field over the baryon(lepton) number of the dark matter field. This means that the dark matter can have a heavier mass if it has a bigger baryon(lepton) number. We demonstrated this possibility by constructing some renormalizable models, where the decaying scalars

directly decay into two or three dark matter scalars while their decays into a number of the SM quarks(leptons) are mediated by some on-shell and/or off-shell scalar bilinears. Our dark matter scalar is consistent with the present dark matter direct detection experiments and can be verified in the future. The required scalar bilinears can also be detected at LHC or ILC. In our examples, we have not discussed explicitly the generation of the decaying scalars, which could be thermally produced by their interactions with other fields. This is the thermal baryogenesis scenario. Alternatively, we can consider the nonthermal baryogenesis, where the decaying scalars are responsible for the chaotic inflation [16].

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\* Electronic address: peihong.gu@mpi-hd.mpg.de

† Electronic address: manfred.lindner@mpi-hd.mpg.de

‡ Electronic address: utpal@prl.res.in

§ Electronic address: xmzhang@ihep.ac.cn

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